Application of the Characteristic Basis Function Method (CBFM) on a Non-Uniform Mesh to the Solution of Large-Size Dielectric Scattering Problems

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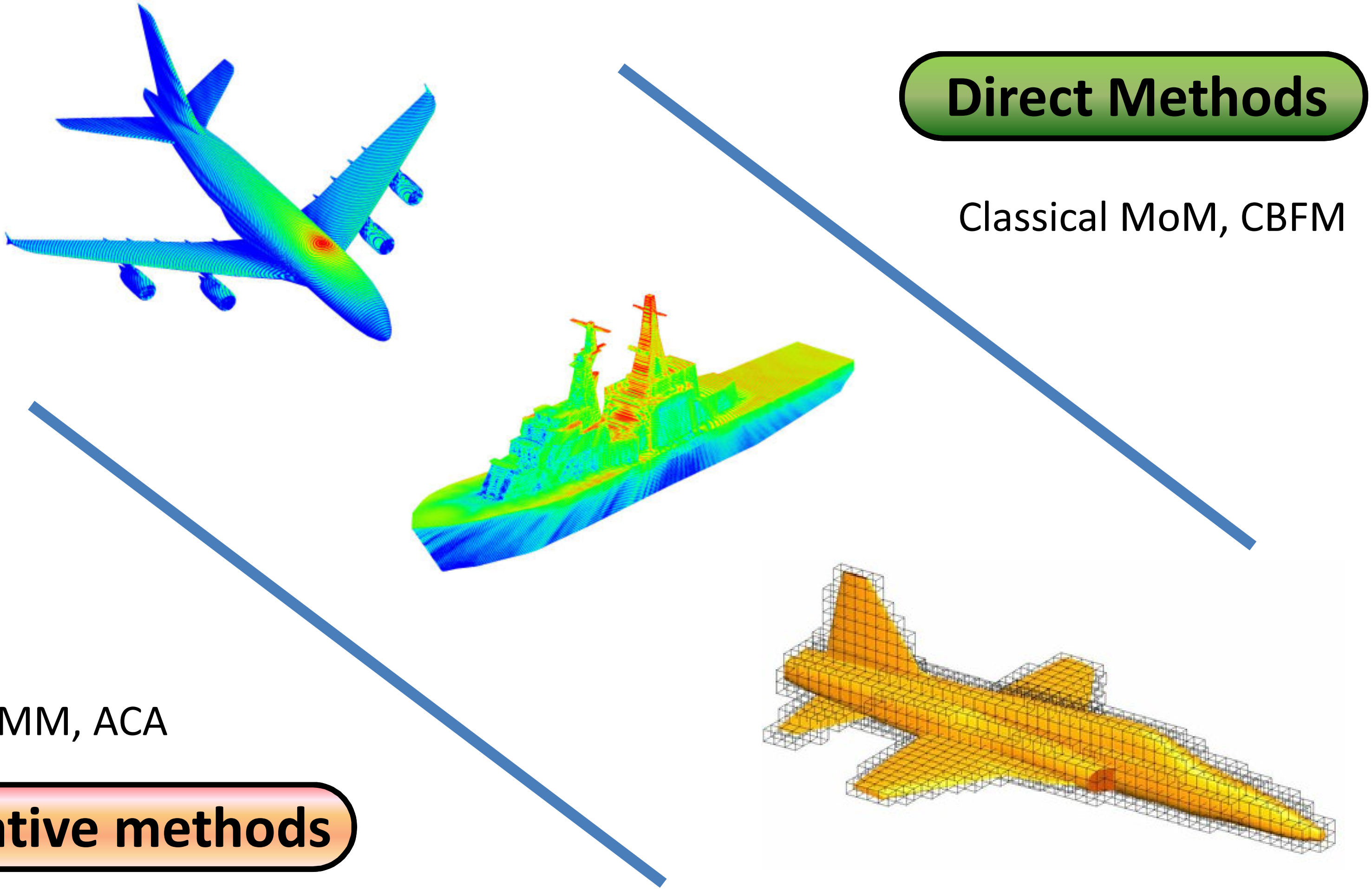
Numerical Methods : direct or iterative ?



Direct Methods

Classical MoM, CBFM

FMM, ACA

Iterative methods

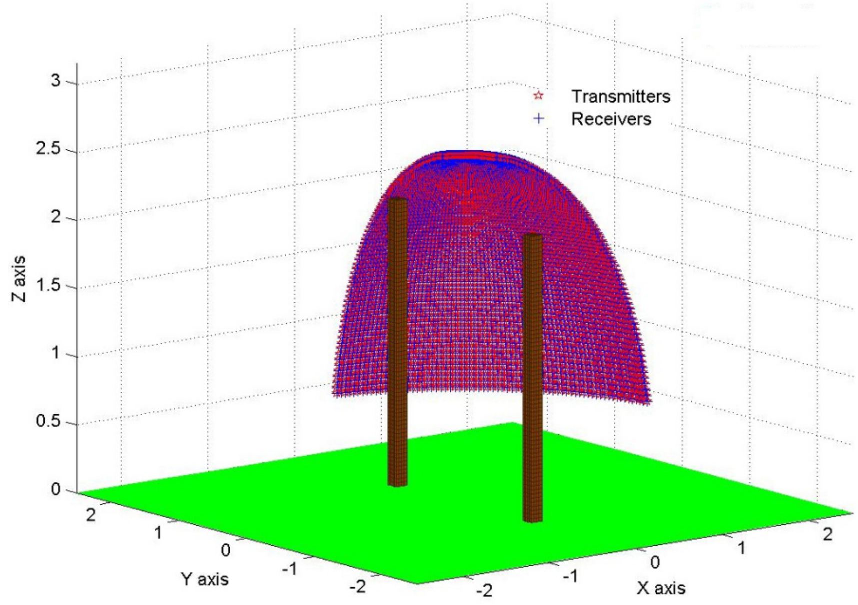
* FEKO : Multilevel Fast Multipole Method (MLFMM), www.feko.info

Numerical Methods : direct or iterative ?

Direct Methods

MoM, CBFM

- Deal better with multiple right hand sides (RHS) problems such as the computation of monostatic radar cross section (RCS).



- Do not suffer convergence problems (due to ill conditionning)
- More robust with respect to numerical errors.

Characteristic Basis Function Method

Direct Methods

CBFM

- A **numerically Efficient** method for solving large electromagnetic Scattering Problems
- It allows **significant reduction** in the number of unknowns which leads to a substantial reduction in the **CPU time** and **memory use**
- The CBFM algorithm is highly amenable to **parallelization** and is also available with a **multilevel scheme** (MLCBFM).

* R. Mittra and K. Du “Characteristic Basis Function Method for Iteration-Free Solution of Large Method of Moments Problems”, EMC Laboratory Penn State University, Progress In Electromagnetics Research B, Vol. 6, 307336, 2008.

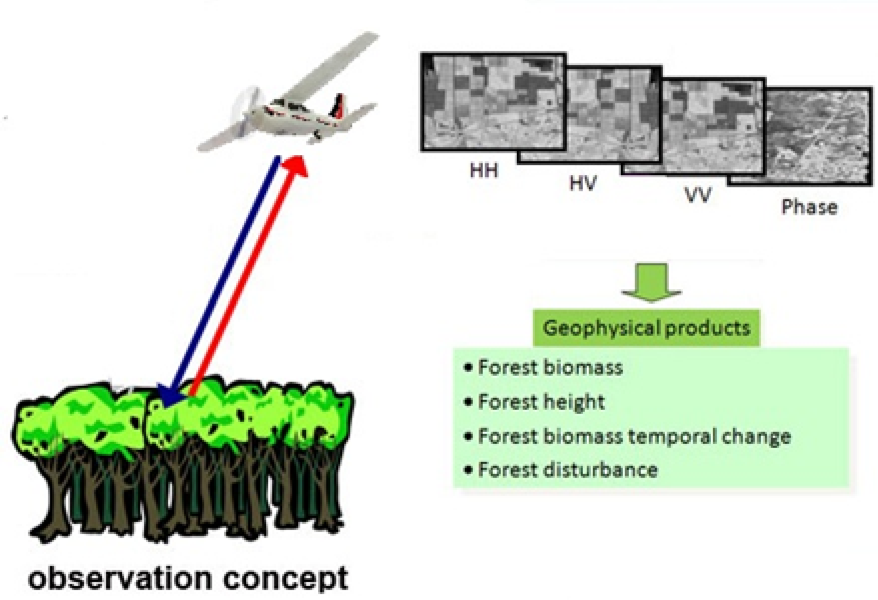
* Jaime Laviada, Fernando Las-Heras, Marcos R. Pino, and Raj Mittra,“Solution of Electrically Large Problems With Multilevel Characteristic Basis Functions”, Department of Electrical Engineering, University of Oviedo and EMC Laboratory Penn State University, IEEE Trans. Antennas Propag., Vol. 57, No. 10, pp.3189-3198, October 2009.

* R. Maaskant, R. Mittra, A. Tijhuis, “Fast Analysis of Large Antenna Arrays Using the Characteristic Basis Function Method and the Adaptive Cross Approximation Algorithm” Antennas and Propagation, IEEE Transactions on , vol.56, no.11, pp.3440,3451, Nov. 2008.

Application to forest scattering modeling

Analysis of forest cover

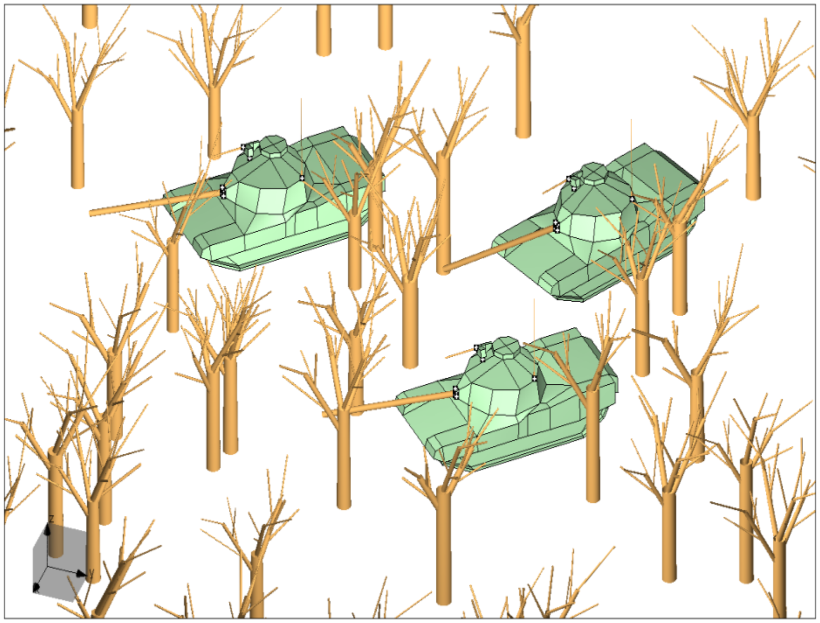
Fields of application



Geophysical products

- Forest biomass
- Forest height
- Forest biomass temporal change
- Forest disturbance

observation concept



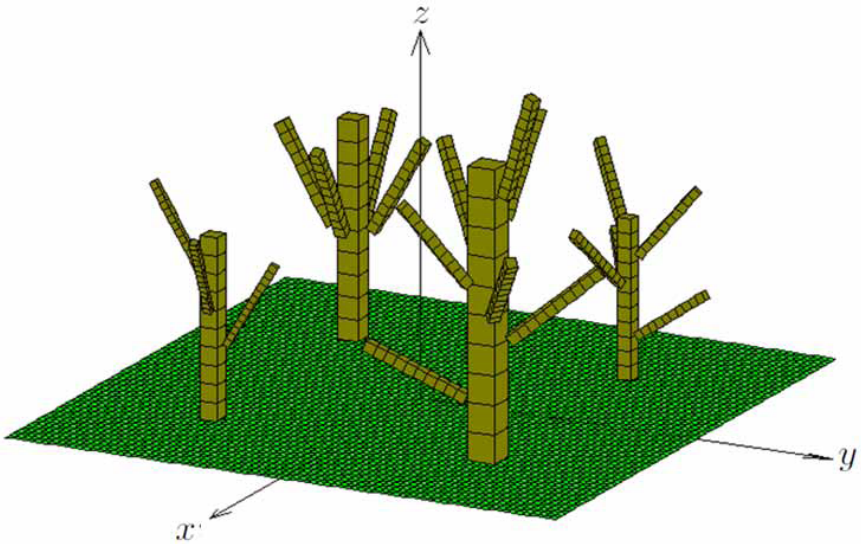
* BIOMASS, Thuy Le Toan, *Journées TOSCA-TropiSAR, Toulouse 19-20 Janvier 2011*

* Model FORESTER, Department of Defense of the U.S. Government and DARPA

Project of Tanks, WIPL-D, www.wipl-d.com, contact@wipl-d.com

Application to forest scattering modeling

3D full-wave model, based on the integral representation of the electric field (EFIE)



* S. Bellez , PhD thesis, UPMC 2010

Discretization of the EM problem into N cells

$$\underbrace{\begin{bmatrix}[Z^{mn}_{xx}] & [Z^{mn}_{xy}] & [Z^{mn}_{xz}]\\ [Z^{mn}_{yx}] & [Z^{mn}_{yy}] & [Z^{mn}_{yz}]\\ [Z^{mn}_{zx}] & [Z^{mn}_{zy}] & [Z^{mn}_{zz}]\end{bmatrix}}_{\underline{\mathbf{Z}}} \underbrace{\begin{bmatrix}[E^{n}_{x}]\\ [E^{n}_{y}]\\ [E^{n}_{z}]\end{bmatrix}}_{\underline{\mathbf{E}}} = \underbrace{\begin{bmatrix}[E^{\mathrm{ref},\,m}_{x}]\\ [E^{\mathrm{ref},\,m}_{y}]\\ [E^{\mathrm{ref},\,m}_{z}]\end{bmatrix}}_{\underline{\mathbf{E}}^{\mathrm{ref}}}$$

✚

Method of Moments (MoM)

- **Problem:** Rigorous numerical method can become untenable when the problem becomes so large as to be computationally expensive both in terms of CPU time and memory.

- **Solution:** **Characteristic Basis Function Method (CBFM)**

Outline

1. Characteristic Basis Function Method (CBFM)

1.1 Motivations and advantages

1.2. Numerical procedure

2. Application of the CBFM on a non-uniform mesh

2.1. Motivations

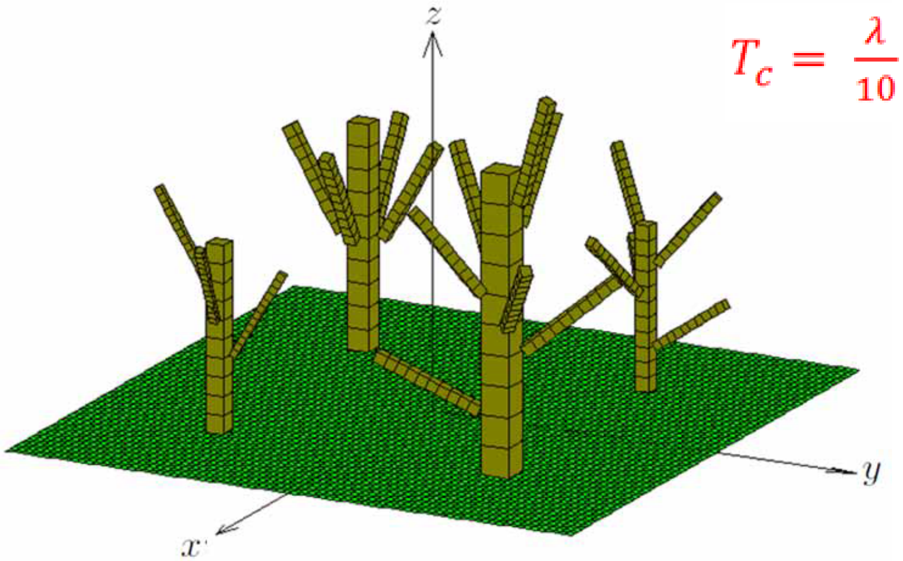
2.2. Numerical Results

3. Conclusions and perspectives

Characteristic Basis Function Method

Motivations and advantages

3D full-wave model, based on the integral representation of the electric field (EFIE)



$T_c = \frac{\lambda}{10}$, $\lambda = \frac{\lambda_0}{\sqrt{Re(\varepsilon_r)}}$

* S. Bellez , Thèse de doctorat, UPMC 2010

Method of Moments (MoM)

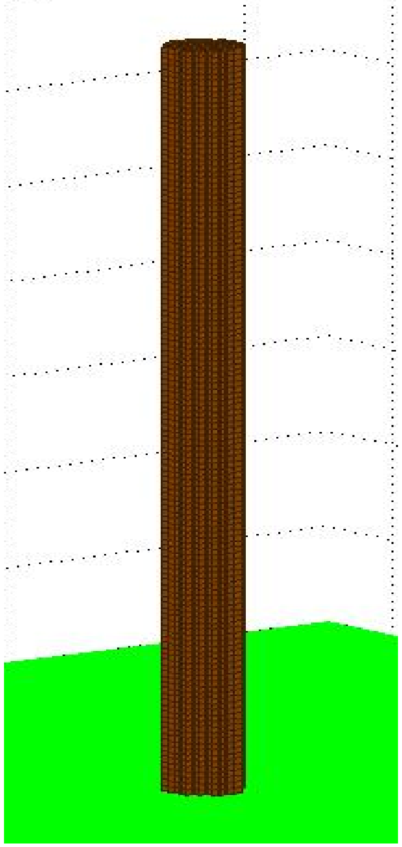
Integral representation of the total electric field :

$$\sum_{n=1}^{N}\sum_{q=1}^{3} Z_{pq}^{mn}\, E_q^{n} = E_p^{ref,m}$$ p,q = x,y,z et m,n = [1,......,Nb_c] $\bar{r}'$

Ω

Motivations and advantages

3D full-wave model, based on the integral representation of the electric field (EFIE)



Tree trunk discretized into N elementary cubic cells.

MoM

$$\left(\begin{array}{ccc}
\begin{bmatrix} Z_{xx}^{11} & Z_{xy}^{11} & Z_{xz}^{11} \\ Z_{yx}^{11} & Z_{yy}^{11} & Z_{yz}^{11} \\ Z_{zx}^{11} & Z_{zy}^{11} & Z_{zz}^{11} \end{bmatrix} & \cdots & \begin{bmatrix} Z_{xx}^{1N} & Z_{xy}^{1N} & Z_{xz}^{1N} \\ Z_{yx}^{1N} & Z_{yy}^{1N} & Z_{yz}^{1N} \\ Z_{zx}^{1N} & Z_{zy}^{1N} & Z_{zz}^{1N} \end{bmatrix} \\
\vdots & \ddots & \vdots \\
\begin{bmatrix} Z_{xx}^{N1} & Z_{xy}^{N1} & Z_{xz}^{N1} \\ Z_{yx}^{N1} & Z_{yy}^{N1} & Z_{yz}^{N1} \\ Z_{zx}^{N1} & Z_{zy}^{N1} & Z_{zz}^{N1} \end{bmatrix} & \cdots & \begin{bmatrix} Z_{xx}^{NN} & Z_{xy}^{NN} & Z_{xz}^{NN} \\ Z_{yx}^{NN} & Z_{yy}^{NN} & Z_{yz}^{NN} \\ Z_{zx}^{NN} & Z_{zy}^{NN} & Z_{zz}^{NN} \end{bmatrix}
\end{array}\right)$$

Z is the **3N**x**3N** matrix representing the **interactions** between the different cells in the object.

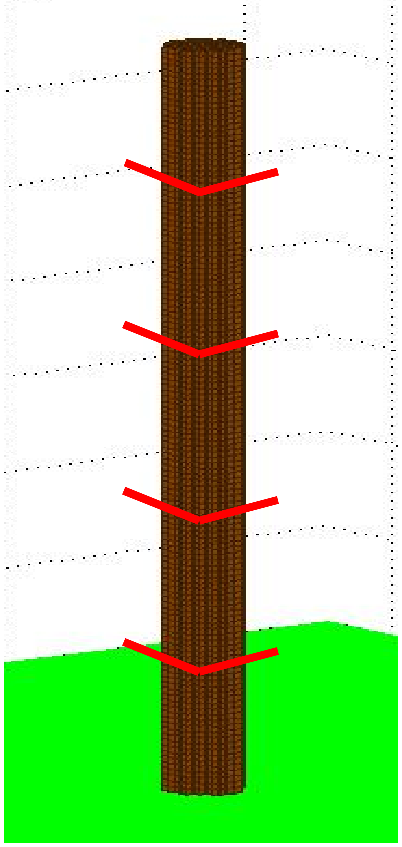
Linear system resolution

The use of this model is limited to few trees and to low frequencies

($N_{max} \approx 13\,000$)

Motivations and advantages

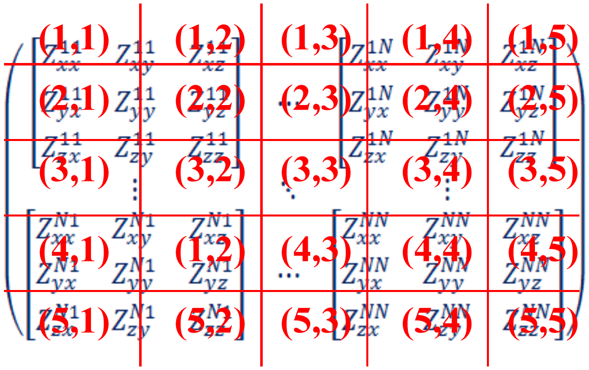
3D full-wave model, based on the integral representation of the electric field (EFIE)



Tree trunk discretized into N elementary cubic cells.

CBFM

Division of the 3D scatterer geometry into M patches


(1,1) (1,2) (1,3) (1,4) (1,5)
(2,1) (2,2) (2,3) (2,4) (2,5)
(3,1) (3,2) (3,3) (3,4) (3,5)
(4,1) (1,2) (4,3) (4,4) (4,5)
(5,1) (5,2) (5,3) (5,4) (5,5)

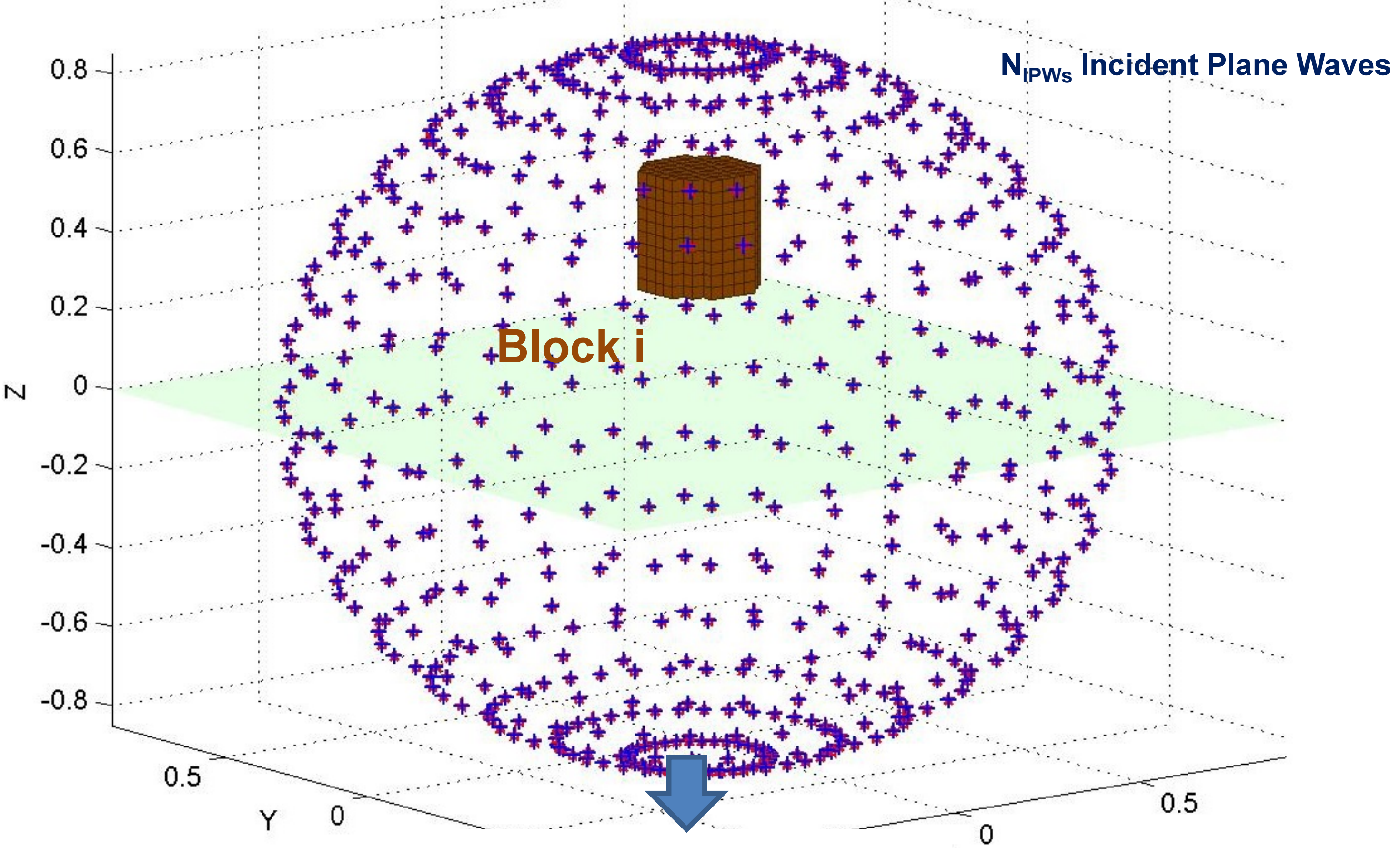
Via CBFM procedure

Reduced matrix

Improvement of the performances of the 3D model in terms of computation time and memory consumption

The CBFM Numerical procedure

Generation of the Macro-Basis Functions (MBFs)

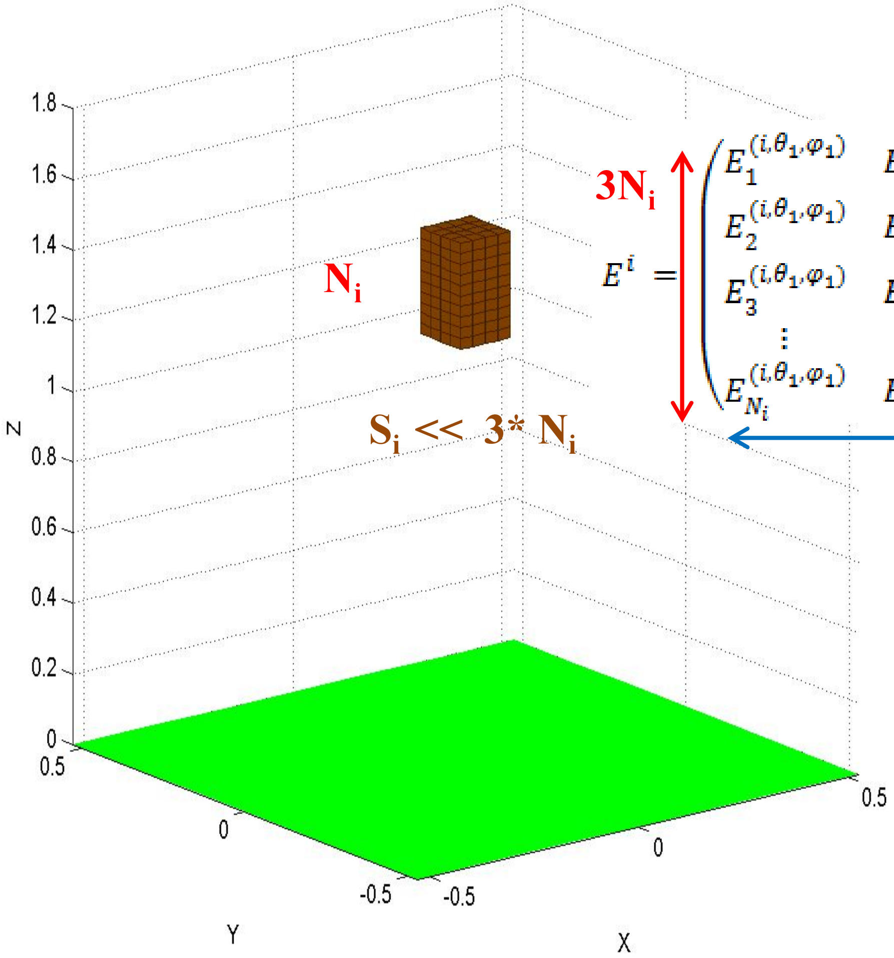


$$Z_{ii} . E_{ii}^{MBFs} = E_{ii}^{ref,IPWs}$$

Numerical procedure

Generation of the Characteristic Basis Functions (CBFs)

Generation of the Macro Basis Functions (MBFs)



N_i

$S_i << 3^* N_i$

$$3N_i \updownarrow \quad E^i = \begin{pmatrix} E_1^{(i,\theta_1,\varphi_1)} & E_1^{(i,\theta_2,\varphi_1)} & \cdots & E_1^{(i,\theta_{N\theta},\varphi_1)} & E_1^{(i,\theta_1,\varphi_2)} & \cdots & E_1^{(i,\theta_{N\theta},\varphi_{N\varphi})} \\ E_2^{(i,\theta_1,\varphi_1)} & E_2^{(i,\theta_2,\varphi_1)} & \cdots & E_2^{(i,\theta_{N\theta},\varphi_1)} & E_2^{(i,\theta_1,\varphi_2)} & \cdots & E_2^{(i,\theta_{N\theta},\varphi_{N\varphi})} \\ E_3^{(i,\theta_1,\varphi_1)} & E_3^{(i,\theta_2,\varphi_1)} & \cdots & E_3^{(i,\theta_{N\theta},\varphi_1)} & E_3^{(i,\theta_1,\varphi_2)} & \cdots & E_3^{(i,\theta_{N\theta},\varphi_{N\varphi})} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ E_{N_i}^{(i,\theta_1,\varphi_1)} & E_{N_i}^{(i,\theta_2,\varphi_1)} & \cdots & E_{N_i}^{(i,\theta_{N\theta},\varphi_1)} & E_{N_i}^{(i,\theta_1,\varphi_2)} & \cdots & E_{N_i}^{(i,\theta_{N\theta},\varphi_{N\varphi})} \end{pmatrix}$$

$\longleftrightarrow$ N_{Ins}

⇩

Singular Value Decomposition (SVD)

+

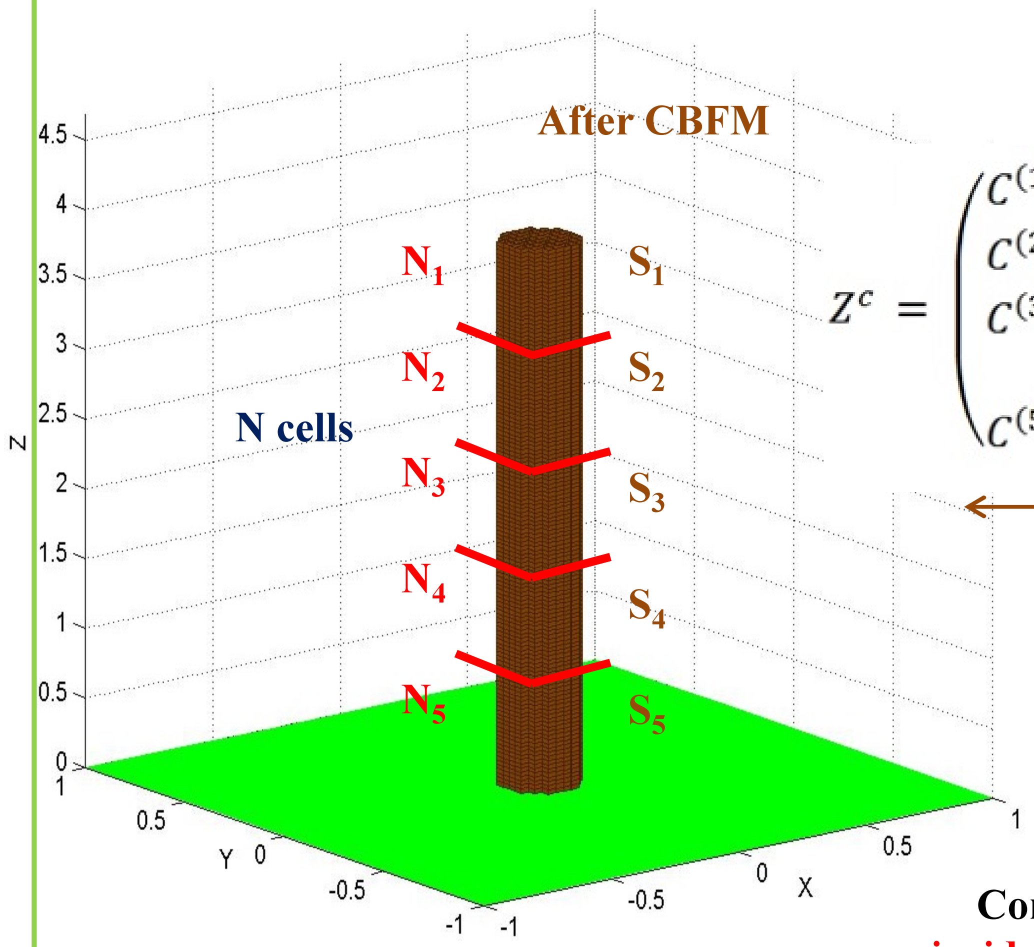
Normalization and thresholding (10^{-3})

=

S_i characteristic basis functions (CBFs) for the block i

The CBFM Numerical procedure

Generation of the reduced matrix equation



$$Z^c = \begin{pmatrix} C^{(1)t} Z_{11} C^{(1)} & \dots & C^{(1)t} Z_{15} C^{(5)} \\ C^{(2)t} Z_{21} C^{(1)} & \dots & C^{(2)t} Z_{25} C^{(5)} \\ C^{(3)t} Z_{31} C^{(1)} & \dots & C^{(3)t} Z_{35} C^{(5)} \\ \vdots & \ddots & \vdots \\ C^{(5)t} Z_{51} C^{(1)} & \dots & C^{(5)t} Z_{55} C^{(5)} \end{pmatrix} \updownarrow K$$

$$\longleftrightarrow$$

$K = S_1 + S_2 + S_3 + S_4 + S_5 \ll 3*N$

⬇

Solving the reduced matrix equation

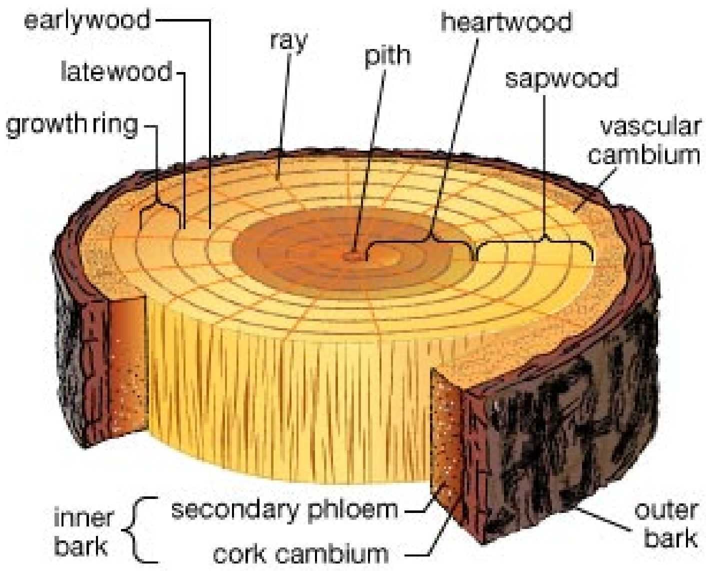
⬇

Computation of the total electric field inside the scatterers and the scattered field

The CBFM applied on a non-uniform mesh

The CBFM applied on a non-uniform mesh

Where does this idea come from ?



earlywood
latewood
growth ring
ray
pith
heartwood
sapwood
vascular cambium
inner bark
secondary phloem
cork cambium
outer bark

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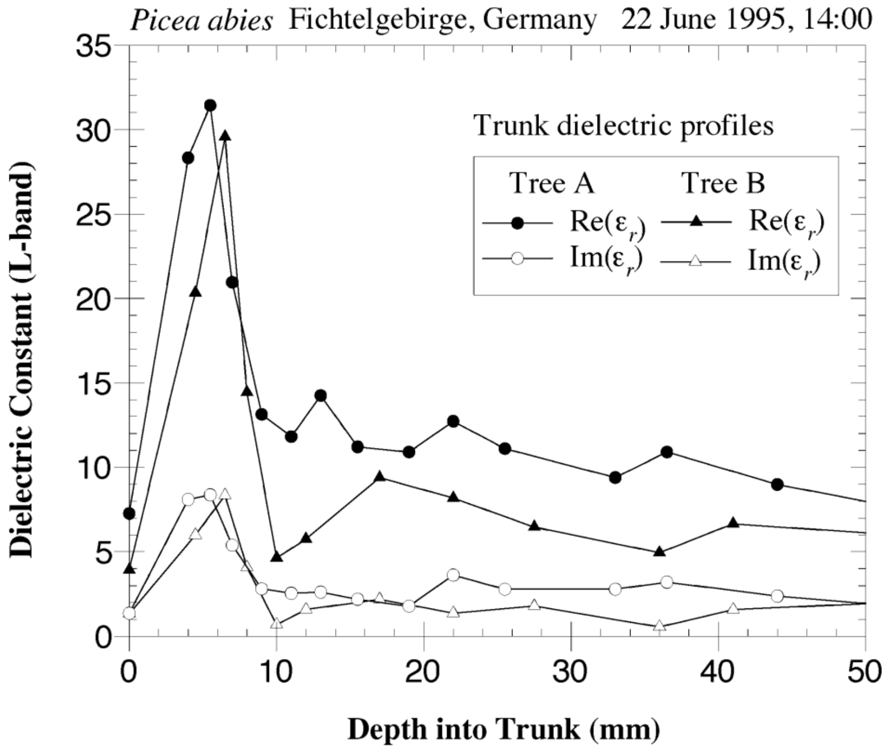
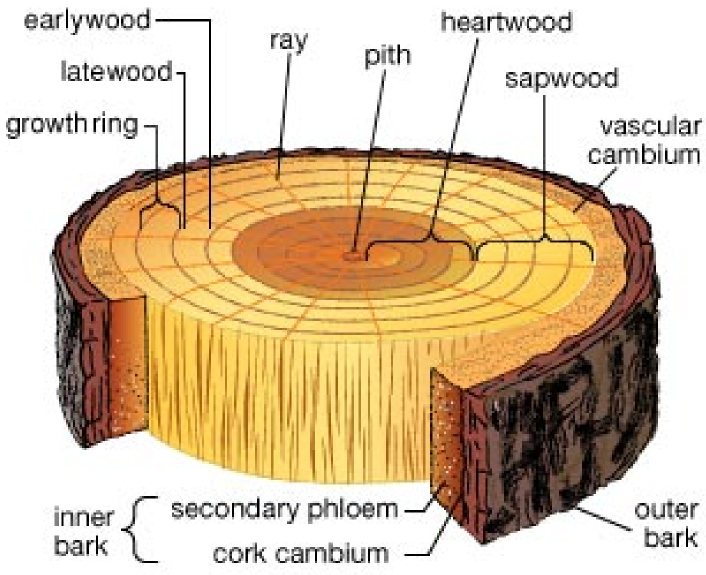


A tree trunk cross section

* Kyle C. McDonald, Reiner Zimmermann, and John S. Kimball "Diurnal and Spatial Variation of Xylem Dielectric Constant in Norway Spruce (Picea abies [L.] Karst.) as Related to Microclimate, Xylem Sap Flow, and Xylem Chemistry", IEEE Transactions on Geoscience and remote sensing, vol. 40, no. 9, September 2002

The CBFM applied on a non-uniform mesh

Where does this idea come from ?


earlywood
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vascular cambium
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secondary phloem
cork cambium
outer bark

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A tree trunk cross section

The trees **dielectric properties** are strongly correlated with moisture status in trunk wood

$$\varepsilon_s = \varepsilon_s' + i\,.\,\varepsilon_s''$$

$$\lambda_s = \frac{\lambda}{\sqrt{\varepsilon_s'}}$$

$$\downarrow$$

$$T_c \leq \frac{\lambda_s}{10}$$

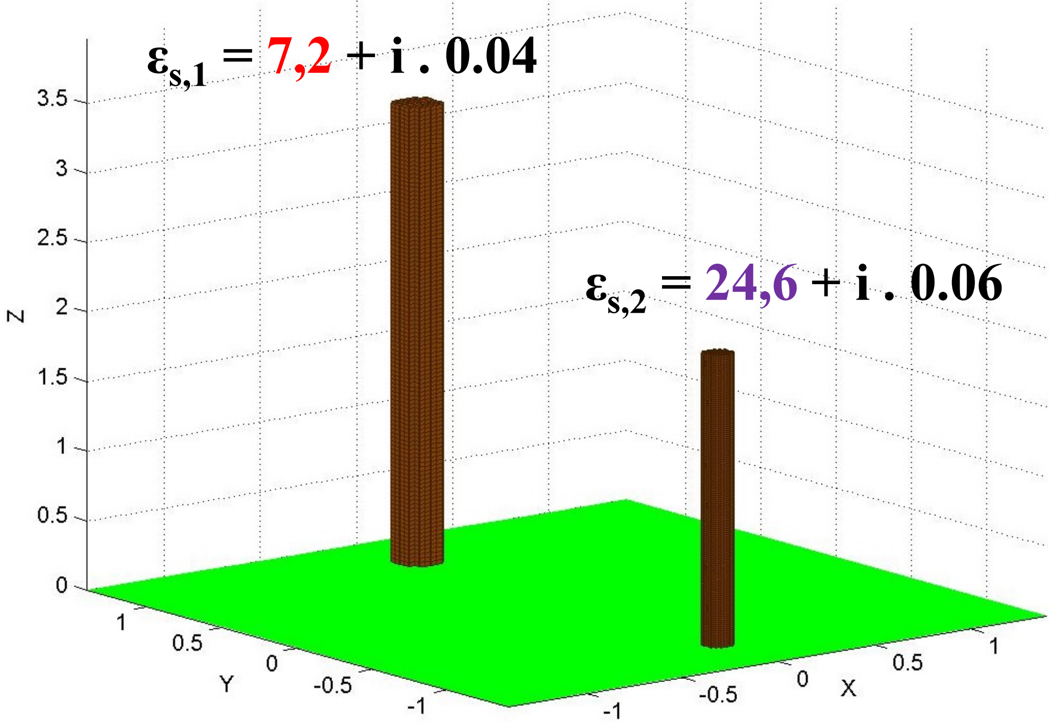
$$\delta_s = \frac{67}{f(MHz)\sqrt{\varepsilon_s''}}$$

$$\downarrow$$

$$T_c \leq \frac{\delta_s}{5}$$

The CBFM applied on a non-uniform mesh

1) A different cell size for each scatterer depending on its dielectric properties



$\varepsilon_{s,1}$ = 7,2 + i . 0.04

$\varepsilon_{s,2}$ = 24,6 + i . 0.06

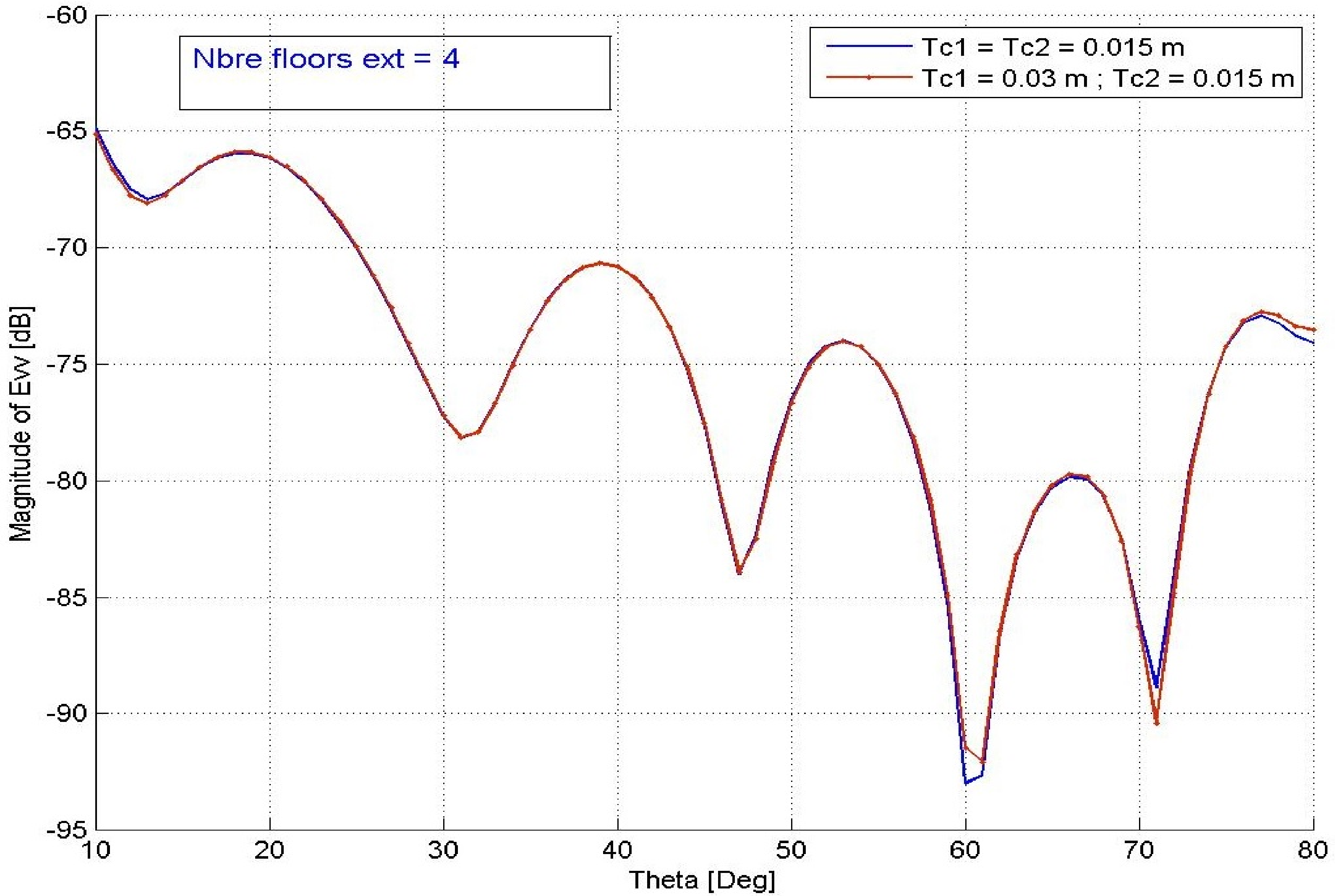
f = 300 MHz

⇩

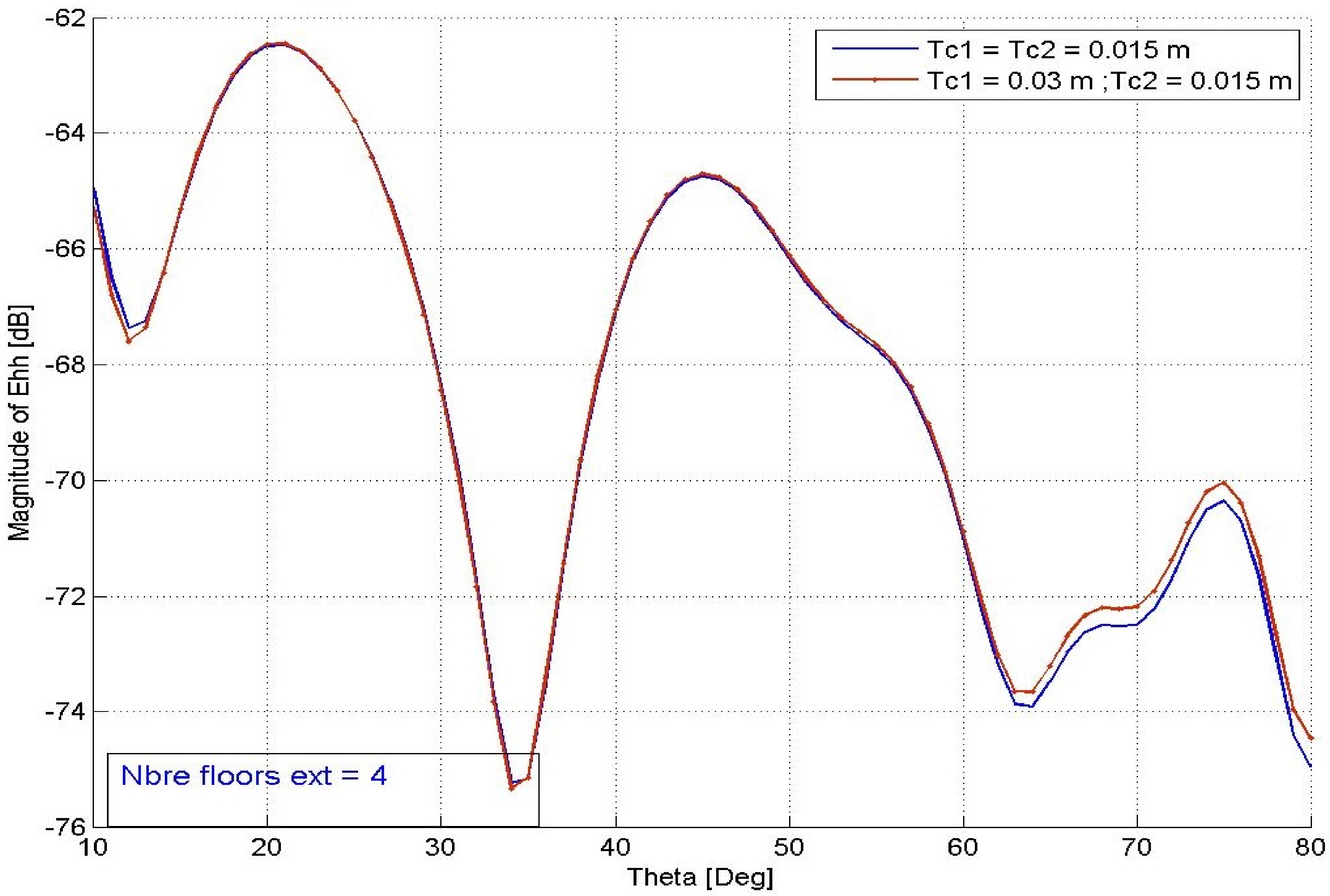
$\lambda_{s,1}$ = 0.37 m
$\lambda_{s,2}$ = 0.20 m

Simulation 1	Simulation 2
$T_{c,1} = T_{c,2} = 0.015$ m -> $N_{bc} = 40640$	$T_{c,1} = 0.03$ m ; $T_{c,2} = 0.015$ m -> $N_{bc} = 12920$

The CBFM applied on a non-uniform mesh

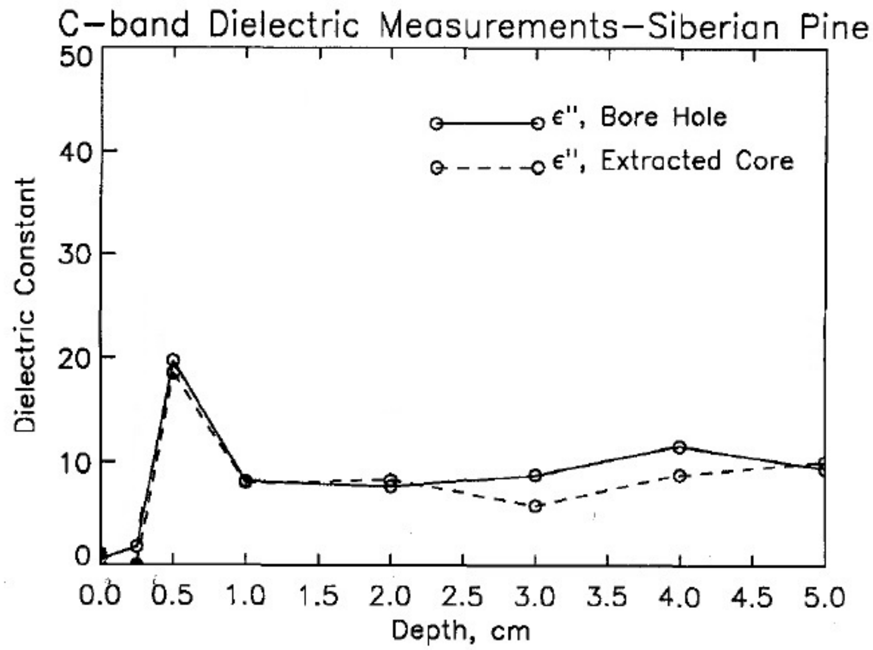


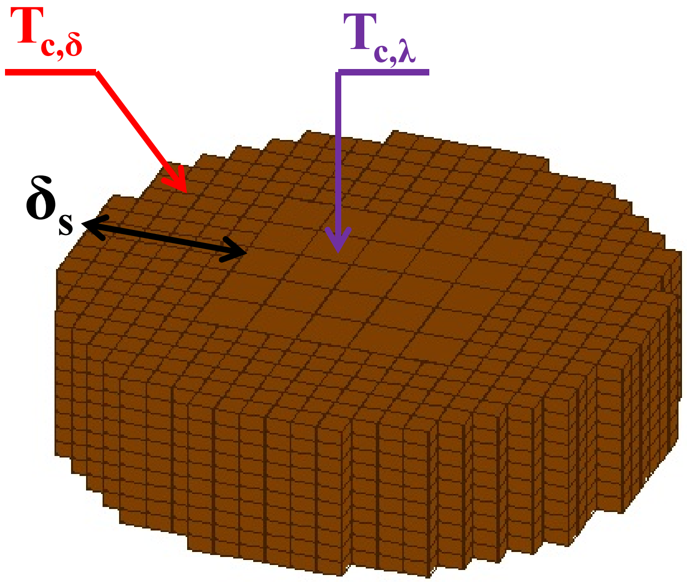
The CBFM applied on a non-uniform mesh



The CBFM applied on a non-uniform mesh

2) Different cell sizes inside the same scatterer

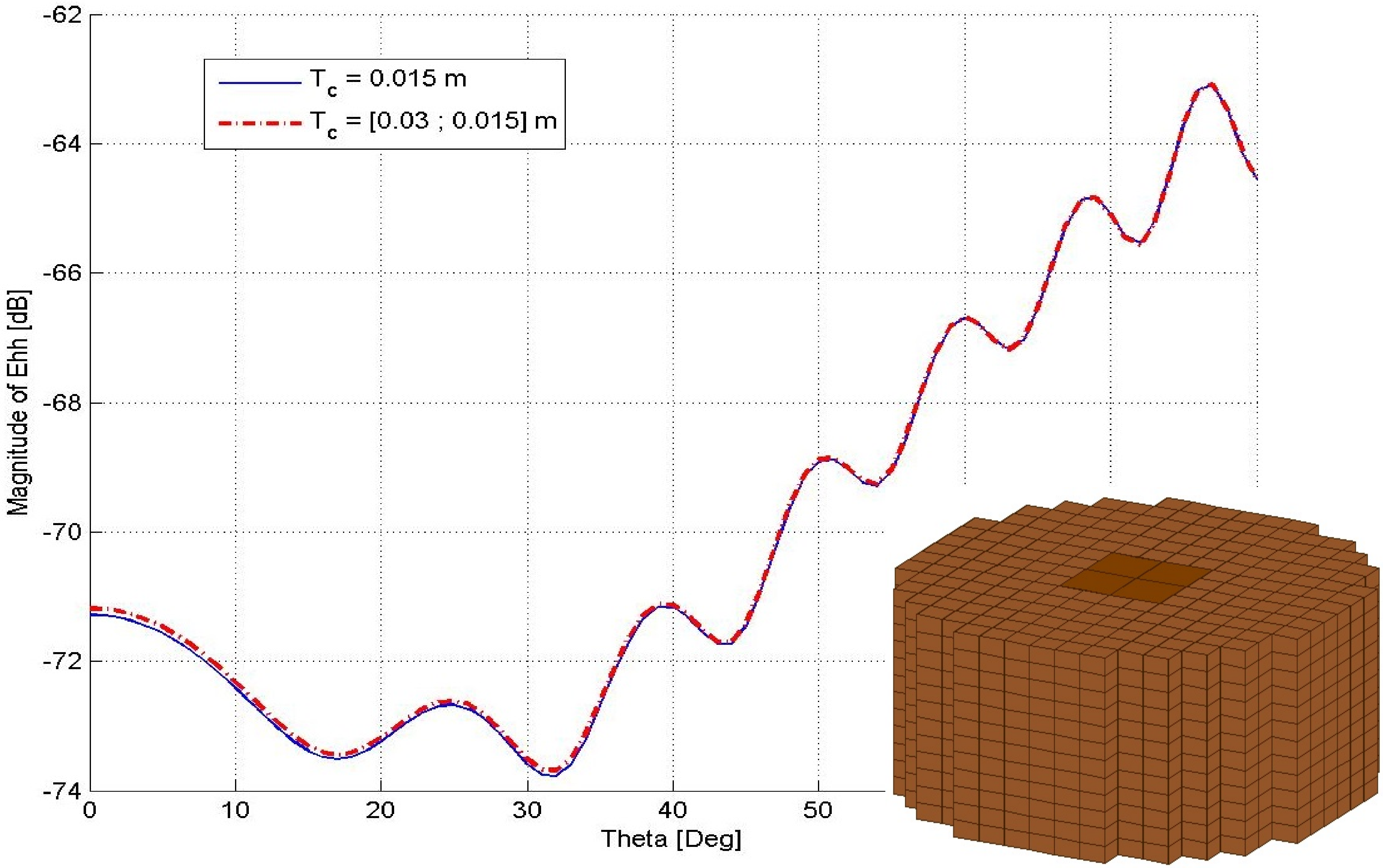




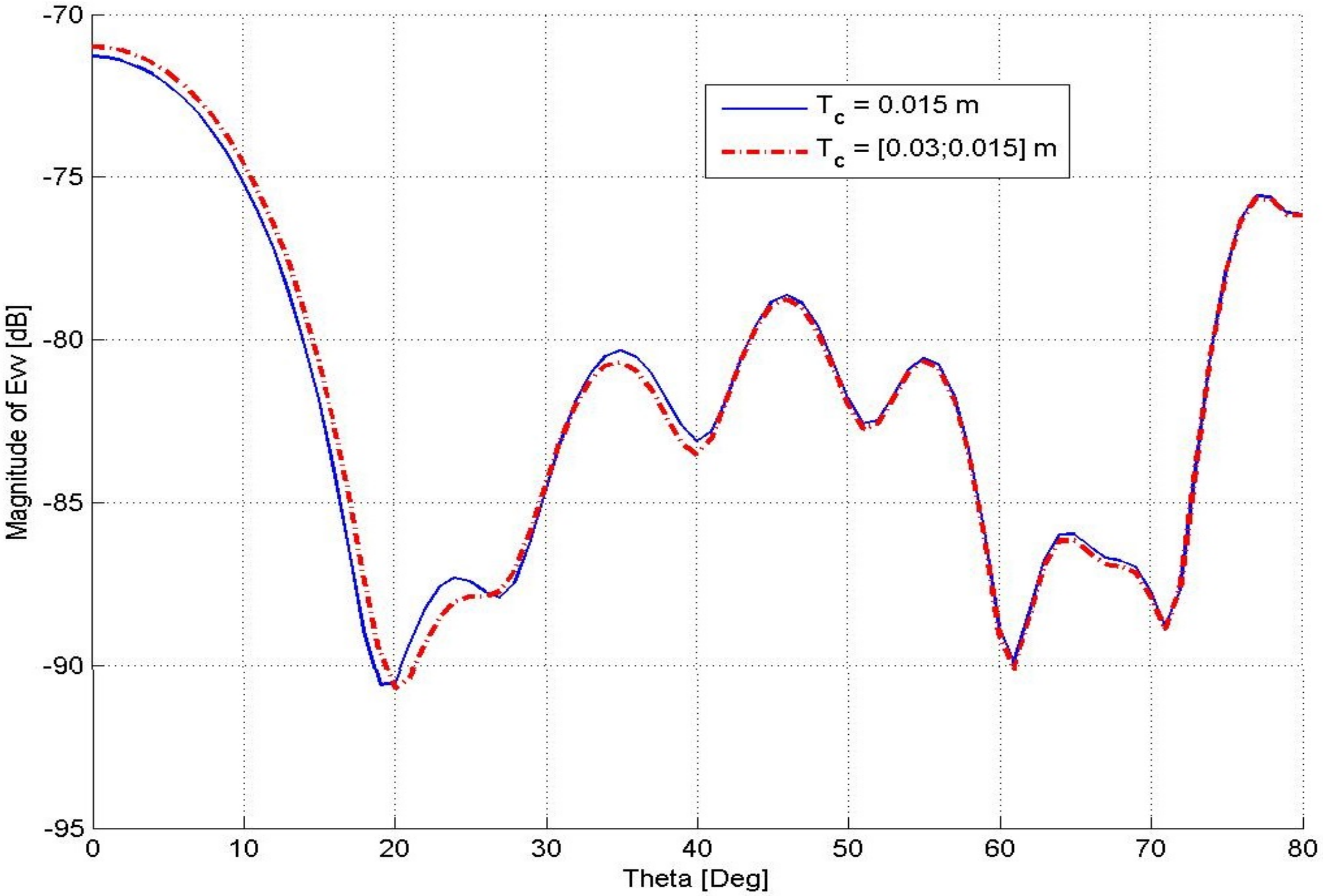
* K. J. Ranson B.N. Rock, W.A. Salas, K. Smith and D.L. Williams "Analysis of the Dielectric Properties of Trunk Wood in Dominant Conifer Species From New England and Siberia", IEEE Transactions on Geoscience and remote sensing, vol. GE 25, no. 5, September 1987

$$\delta_s = \frac{67}{f(MHz)\sqrt{\varepsilon_s''}} \rightarrow T_c \leq \frac{\delta_s}{D_\delta}$$

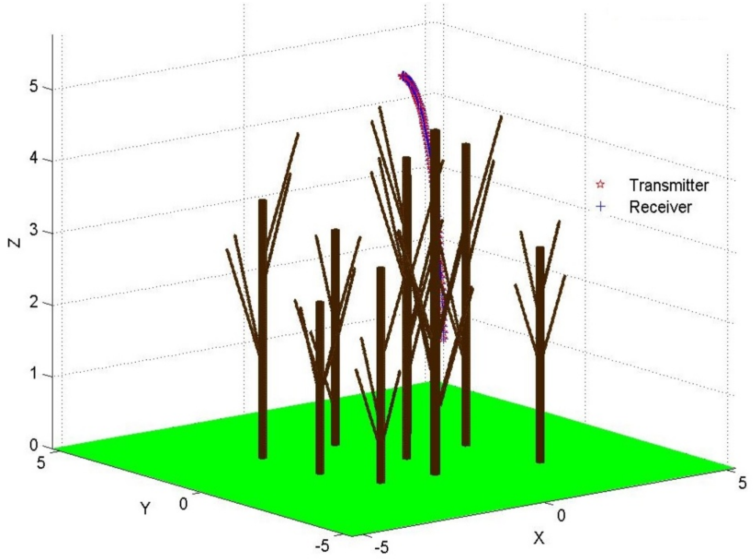
The CBFM applied on a non-uniform mesh



The CBFM applied on a non-uniform mesh



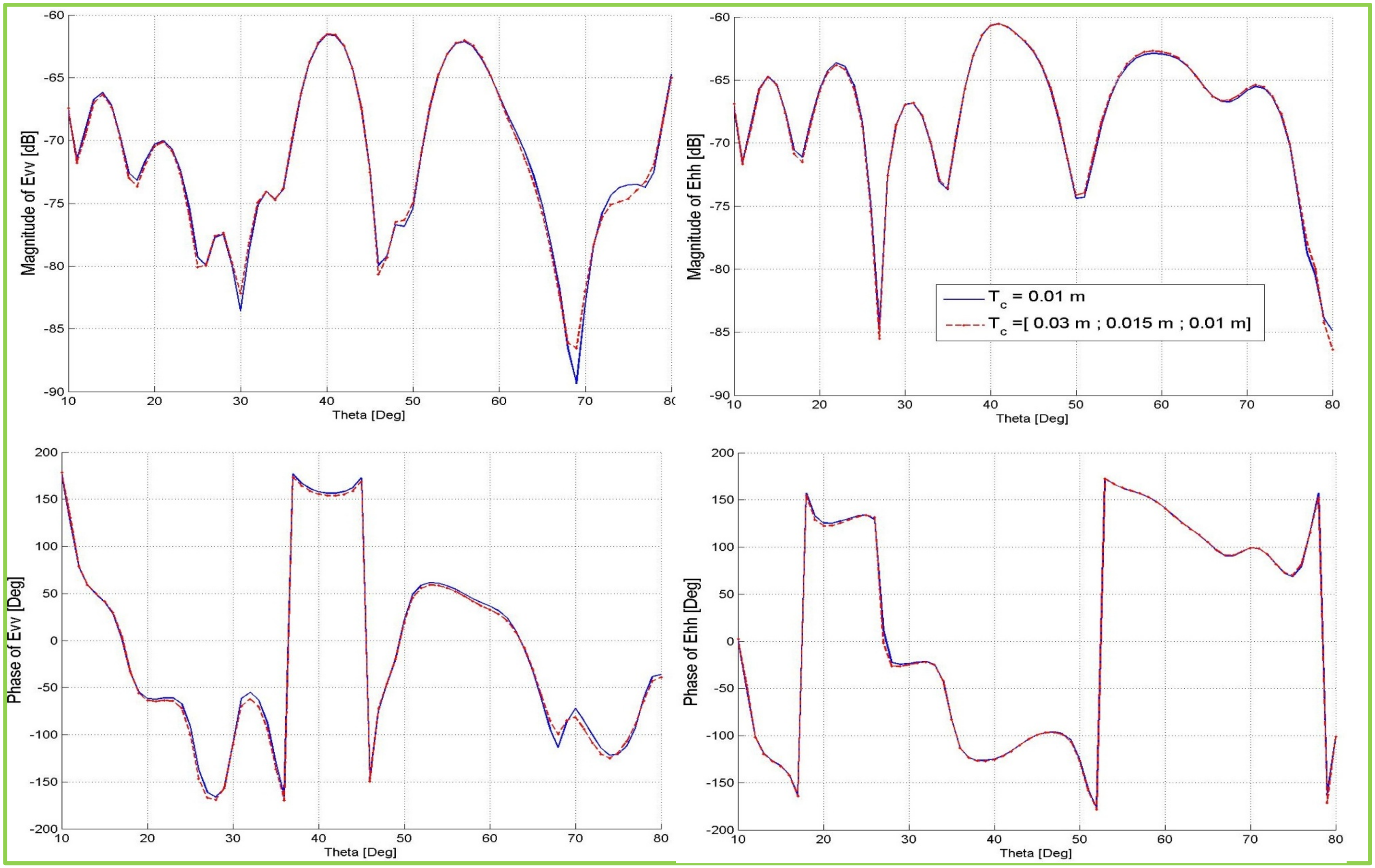
Numerical Results



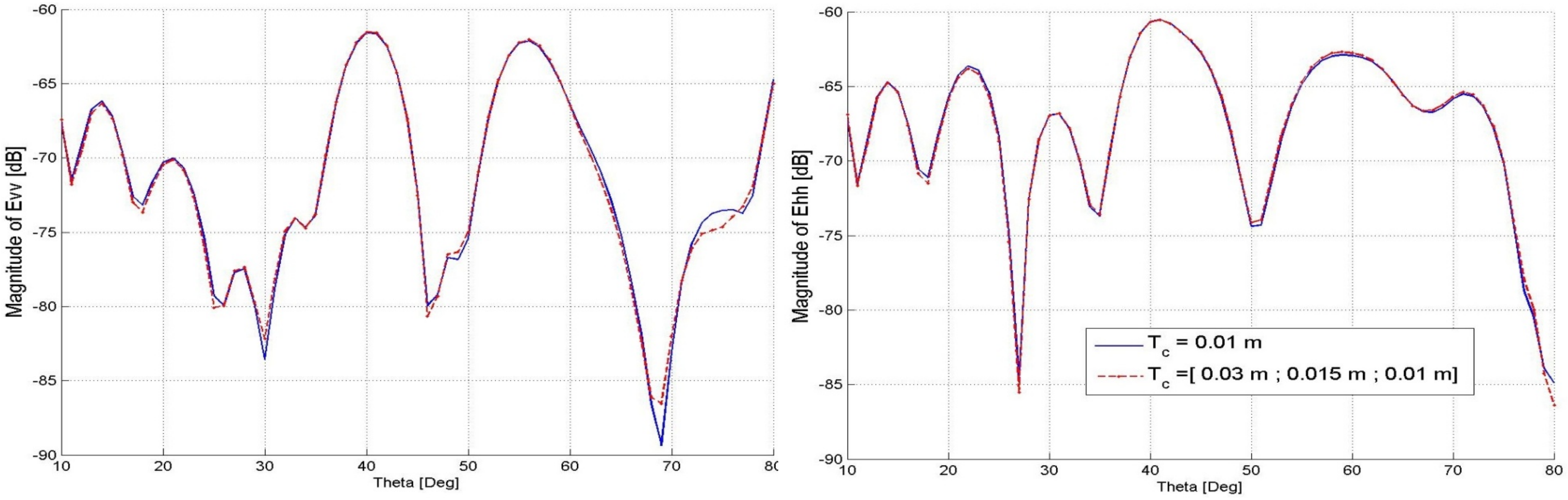
Simulation : 45 cylinders modeling 9 trees with 4 branches each

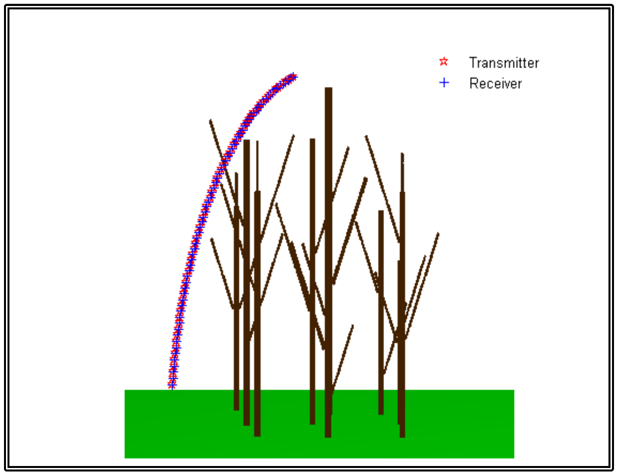
Frequency	300 MHz
Number of cylinders	45
Scatterers Permittivity	$2.9 < \varepsilon_s' < 24.1$ $\varepsilon_s'' = 0.9$
Ground permittivity	$5 + i * 2.1$
λ scatterer	0.58 m $< \lambda_s < 0.20$ m
Size of cells	0.03 m ; 0.015 m ; 0.01 m
N cells	171340
N cells ($T_c = 0.01$ m)	565920
N_z floors per block	10
N_z extended floors	4
N_{IPW}	380
Threshold σ	10^{-3}

Numerical Results



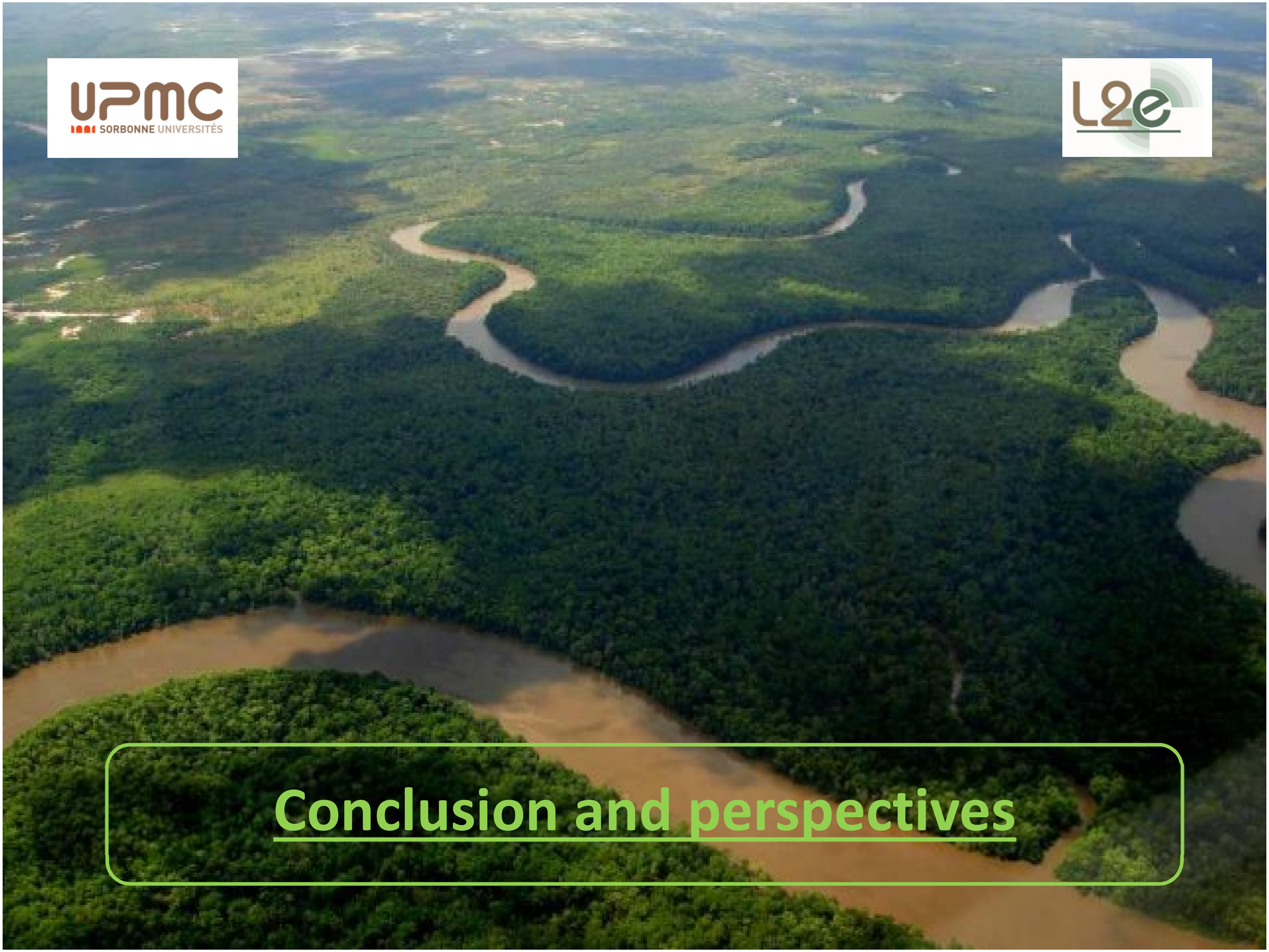
Numerical Results





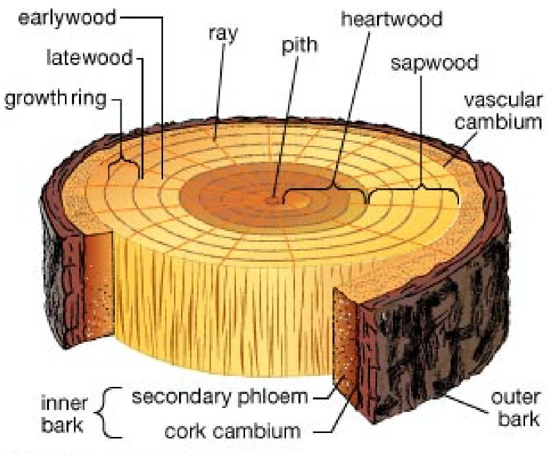
Transmitter
Receiver

	Uniform	Non Uniform
Size of the EM problem	1.709.760	514.020
Computing time	45 h 15 min	4 h 12 min



Conclusion and perspectives

Conclusions and perspectives


earlywood
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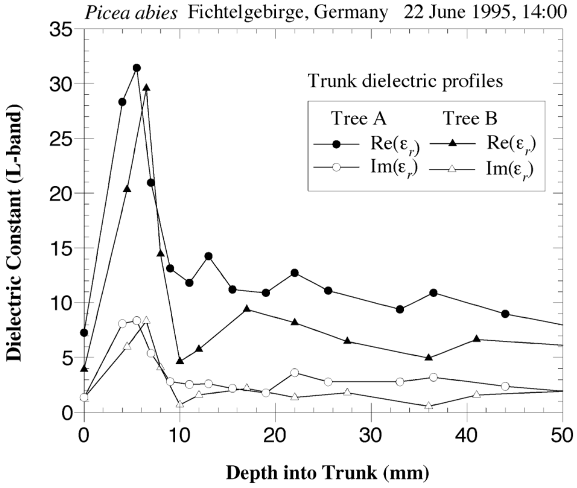
Picea abies Fichtelgebirge, Germany 22 June 1995, 14:00

Conclusions

❖ The CBFM keeps a satisfactory level of accuracy when applied to a **non-uniform mesh** in order to take into account the dielectric properties of the tree trunks.

❖ The CBFM allows to consider larger forest simulation scene for higher frequency thanks to its suitability to the **non-uniform mesh**.

Perspectives

❖ To improve the implementation of the **non-uniform mesh** in order to fit with the different layers which compose a tree trunk .

❖ To compare the performances of the CBFM to those of the ACA when applied to our inhomogeneous dielectric problem.

Thanks for your attention